Renewable and Sustainable Energy Reviews 29 (2014) 473–481

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Renewable energy potential on marginal lands in the United States

Anelia R. Milbrandt [a,*], Donna M. Heimiller [a], Andrew D. Perry [a], Christopher B. Field [b]

[a] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA
[b] Department of Global Ecology, Carnegie Institution, 260 Panama Street, Stanford, CA 94305, USA

ARTICLE INFO

Article history:
Received 27 March 2013
Received in revised form
19 August 2013
Accepted 24 August 2013
Available online 23 September 2013

Keywords:
Renewable energy
Renewable resources
Marginal lands

ABSTRACT

This study identifies several marginal land categories suitable for renewable energy development, representing about 11% of U.S. mainland. The authors define marginal lands as areas with inherent disadvantages or lands that have been marginalized by natural and/or artificial forces. These lands are generally underused, difficult to cultivate, have low economic value, and varied developmental potential. The study finds that a significant potential exists for renewable energy development on these lands. Technologies assessed include utility-scale photovoltaics (PV), concentrating solar power (CSP), wind, hydrothermal geothermal, mini-hydro systems (low head/low power), biomass power, and landfill gas-to-energy. Solar technologies present the highest opportunity, followed by wind and biomass power. It is estimated that about 4.5 PWh of electricity could be produced from PV on marginal lands in the conterminous United States, 4 PWh from CSP, 2.7 PWh from wind, 1.9 PWh from biomass, 11 TWh from mini-hydropower systems, 8.8 TWh from hydrothermal geothermal, and 7.3 TWh from landfill gas. While it is possible for some technologies to be co-located, it is more likely that only one will be deployed in a given area. Thus, it is most reasonable to view the potential for different technologies separately.

Contents

1. Introduction

The production of renewable energy is increasing in the United States. A study by the Natural Resources Defense Council estimates an increase of more than 300% in the past decade [1]. Development of additional renewable generation capacity will require land access that could put pressure on available land resources; a single plant can have a considerable footprint based on the size and technology employed. For example, the 250 MW Abengoa Mojave concentrating solar plant covers an area of about 7 km^2. Additionally, land prices for prime farmland and other desirable lands could be prohibitive for development. These considerations have encouraged the search for alternative options such as the use of lands with few or no competing uses. Installing renewable energy systems on these lands could provide environmental and socio-economic benefits while expanding the country's clean energy supply. For example, the reuse and redevelopment of abandoned or contaminated sites could improve communities, create jobs, and decrease the use of more valuable land for renewable energy plants. Marginal lands offer certain advantages to the renewable energy industry. Typically, these sites are relatively inexpensive. They can also be large enough to allow technologies to scale up, and be located near critical infrastructure like roads, power lines, and water supply.

Many studies have documented renewable energy resource estimates for the United States but none have looked exclusively at the various marginal lands in the country. There are few related

* Corresponding author. Tel.: +1 303 275 4633.
E-mail address: anelia.milbrandt@nrel.gov (A.R. Milbrandt).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.08.079

studies but they are limited in scope – focused on a single technology [5] and/or one type of marginal land [3,5]. The main objectives of this study are to define and identify the marginal lands in the United States and assess their renewable energy potential. It seeks to provide policy makers and industry developers with a better understanding of the marginal lands availability and thus guide their future strategic investment and policy decisions.

2. Analysis methodology

A literature review and analysis of land use and land cover databases were conducted in order to define and identify marginal lands in the United States. Geospatial data on select marginal land categories were obtained and geographic information systems (GIS) techniques were used to process, summarize, and map the gathered information. GIS was also used to assess the renewable energy potential on those lands.

2.1. Marginal lands in the United States

For the purpose of this study, the authors define marginal lands as lands with inherent disadvantages or lands marginalized by natural and/or artificial forces. These lands are generally underused, difficult to cultivate, have low economic value, and varied developmental potential. There are many other names given to low-quality lands or lands with few or no competing uses such as abandoned, disturbed, underutilized, wasteland, limbo land, degraded, and idle. These may or may not be interchangeable terms. The authors consider “marginal” to be the most inclusive term that encompasses all land categories described below.

Abandoned lands are lands that were previously used for human-related activities (agriculture, forestry, mining, etc.) but are no longer in use due to economic, social, political, or environmental reasons. *Disturbed lands* suggest a human intervention, where the natural ecosystems have been altered or modified, as with mining or oil drilling. These lands do not rehabilitate naturally in the short term because their topsoil has been altered, inverted, or lost [2]. *Underutilized lands* may have the potential to be productive but for economical or physical (e.g. accessibility) reasons, they are not. *Wastelands* are generally associated with barren lands, lack of vegetation, and often are uncultivated and desolate. *Limbo lands* imply lands with uncertain status. The U.S. Environmental Protection Agency (EPA) uses this term to define underused, formerly contaminated sites [3]. *Degraded lands* are defined as lands with reduced or lost biological or economic productivity and complexity [4]. Land degradation can be human-induced or result from natural processes. *Idle lands* are lands currently not in use. While the term does not connote a quality evaluation, in reality, prime land is rarely vacant for long.

There are many land features within the categories described above. However, only a subset of these features are considered in this study:

Abandoned cropland (AC) data were obtained from the University of California – Merced. Zumkehr and Campbell define ACs as lands that were once used for the production of agriculture, but have been released and left to nature [5]. Specific ACs were not identified; rather, a percentage of land area within a grid cell with a spatial resolution of 5 min latitude and longitude (about 8 km) was estimated. It should be noted that AC data were available for the contiguous 48 states only, not for Alaska and Hawaii. The data received did not distinguish current usage of the AC areas.

Abandoned mine lands (AML) include areas where mining activities are temporarily inactive. Data on those lands were obtained from the Bureau of Land Management (Abandoned Mine Lands Portal), Office of Surface Mining (Abandoned Mine Land Inventory System), and EPA (RE-Powering America's Land: Renewable Energy on Potentially Contaminated Land and Mine Sites). Many of the AML records were missing information on area covered. Based on the distribution of areas for records that did contain size (range: 40 m^2–2000 km^2; median: 0.08 km^2 or 8 ha), a conservative default value of 4000 m^2 or 0.4 ha was applied to those sites. The AMLs were provided with a point location; a circular buffer was generated around each point to represent the area associated with the record. Duplication between the sources is expected, but could not be resolved on an individual basis. Instead, overlapping areas were dissolved to reduce the potential impact.

EPA sites include Brownfield, federal/non-federal Superfund, and sites under the Resource Conservation and Recovery Act (RCRA). Data was obtained from EPA's RE-Powering America's Land: Renewable Energy on Potentially Contaminated Land and Mine Sites Project. Brownfield is a site that was previously used for industrial or commercial purposes and may have presence of environmental contaminants. Superfund sites are more severely contaminated. These sites were designated by the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), a United States federal law designed to address hazardous waste sites. Similarly, the RCRA program is concentrated on the proper management of hazardous wastes. A key difference between RCRA and Superfund sites is that states have the primary responsibility for RCRA locations, whereas the federal government is responsible for CERCLA sites. Another difference is that RCRA focuses on controlled facilities whereas CERCLA's focus is on abandoned, uncontrolled hazardous waste sites. These sites have the potential to be reused once they are cleaned up. Similar to the AMLs, a portion of these EPA land records were missing information on area covered. Based on the distribution of areas for records that did contain size information, conservative default values were applied: 2000 m^2 or 0.2 ha to Brownfields (range: 40 m^2–17 km^2; median: 3000 m^2 or 0.3 ha); 40,000 m^2 or 4 ha to RCRA sites (range: 364 m^2–8000 km^2; median: 0.26 km^2 or 26 ha); and 60,000 m^2 or 6 ha to Superfund sites (range: 40 m^2–1470 km^2; median: 121,000 m^2 or 12 ha). These locations again were represented as points, and a circular buffer was generated around each point to represent the area associated with the record. Overlapping areas between categories were dissolved to avoid double counting.

Landfills are sites where waste material is disposed of by burying it under soil. Because landfills are airtight, they have no oxygen, which causes bacteria to break down the waste and release gas, called landfill gas (LFG) or biogas. LFG is typically 50% methane, 45% carbon dioxide and 5% other gases. LFG, namely methane, could be captured and used to generate electricity on site which otherwise would be released into the atmosphere or burned off in a flaring process. According to the EPA, hundreds of LFG energy projects currently operate in the United States. This analysis focuses on the potential LFG projects across the country which EPA calls candidate sites. These are locations accepting waste or that have been closed for five years or less, have at least one million tons of waste, and do not have an operational or under-construction LFG-capturing project [6]. Candidate landfills are also designated based on actual interest or planning by potential developers. Data on the candidate landfill locations was obtained from the EPA's Landfill Methane Outreach Program (LMOP).

Right-of-Ways (*ROWs*) are strips of land along transportation or distribution infrastructure, allowing for maintenance or expansion. ROWs in this study were evaluated for rail, roads, and transmission lines. Railway lines were extracted from the Bureau of Transportation Statistics' U.S. National Transportation Atlas 2005. A single ROW distance of 30 m was chosen for all national railway lines.

Table 1
Technology Assumptions Used from Lopez et al. for Solar, Geothermal, Wind, and Hydropower Technologies.

Technology	Resource threshold	Exclusions	Installation density	Capacity factor
Solar PV	None	Slope > 3%, parks, water, wetlands, forests, federal protected lands	48 MW/km^2	By state, 10.5–26.3%
Solar CSP	Annual average ≥ 5 kWh/m^2/day	Slope > 3%, parks, water, wetlands, forests, federal protected lands	32.9 MW/km^2	By resource class, 31.5–44.8%
Geothermal	Identified conventional; EGS temperature at depth ≥ 150 °C	Limited to areas between 3 and 10 km below the surface; federal protected lands	By temperature 0.59–1.19 MW/km^2	90%
Wind	Gross capacity factor ≥ 30%	Slope > 20%, parks, water, wetlands, urban areas, airports, federal and state protected lands	5 MW/km^2	Modeled for IEC class II wind turbine, 30–65%
Hydropower	Low power (< 1 MWa) and small hydro (≤ 30 MWa)	Site accessibility, parks, wilderness areas, and selected land use and environmentally sensitive areas	Modeled for each site	Modeled for each site

Roads were extracted from the Navteq 2010 North American Streets database. The width of the ROW varies from 15 m for major arteries, such as interstates and U.S. highways, and 12 m for other roads. Within that ROW, an area representing the actual lanes themselves was eliminated at the center, assuming 3.7 m per lane (one lane in each direction). Road features with three or more lanes were excluded from the analysis given that they appear predominately in urban areas, which are not part of this study as described below.

Transmission line data were extracted from the Ventyx Energy Velocity Suite 2012 Energy Map dataset. The ROW was defined by the line voltage, as described by the Tennessee Valley Authority [7]. Based on this input, the transmission line ROW buffer distance varies from about 23 m for lines under 100 kV to 61 m for lines 500 kV or larger, with DC lines falling at 46 m.

Barren lands consist of bare rock, gravel, sand, silt, clay or other earthen material with little or no vegetation present [8]. Data were obtained from the U.S. Geological Survey's National Land Cover Database 2006 with a spatial resolution of 30 m.

2.2. Renewable energy potential on marginal lands

This study estimates the potential energy on marginal lands for utility-scale photovoltaics (PV), concentrating solar power (CSP), wind, hydrothermal geothermal, mini-hydro systems (low head/ low power), biomass power, and LFG. GIS was used to integrate marginal land and renewable resource data, as well as estimate potential nameplate capacity and net generation.

Each renewable energy technology is limited by technology-specific criteria including minimum resource intensity, broadly suitable site characteristics (e.g. slope, land cover), and compatible land use (e.g. excluding protected areas like parks and wildlife refuges). These criteria primarily represent the technical resource potential, but include some economic criteria (e.g. resource intensity, which influences a site's capacity factor and resulting levelized cost of energy). The underlying screened resource datasets, energy conversion, and capacity factor assumptions are drawn from Lopez et al. [9] with the exception of biomass resource data and LFG. A summary of major assumptions from Lopez et al. are listed in Table 1.

For biomass, the potential for growing energy crops on marginal land was evaluated using crop yield estimates by county. No woody crops were included, only three herbaceous crops: miscanthus, switchgrass, and sorghum. Average miscanthus yield data by county were obtained from the Energy Biosciences Institute's Biofuel Ecophysiological Traits and Yields Database [10]. The yield is naturally higher in areas with abundant precipitation such as the Eastern States and North West, where it reaches 20 t/acre and even 30 t/acre in some counties. Miscanthus yield is very low in the arid Rocky Mountain States, barely reaching half a ton/acre. To put things in perspective, a dry ton of biomass typically yields about 1 MWh of electricity. Using the country's average of 15 t/ acre, an acre of miscanthus could generate about 12 MWh of electricity, assuming moisture content of 10% and accounting for some collection and conversion inefficiencies. The U.S. Department of Energy's Oak Ridge National Laboratory provided average yield data for switchgrass and sorghum by county [11]. Similarly to miscanthus, these crops have high yield in the Eastern States and North West (reaching more than 8 t/acre in some counties), and very poor performance in the dry West. In this study, if multiple energy crop types were present in a county, their yield values were averaged.

Estimates of potential capacity at candidate landfills were provided by the EPA, which were subsequently converted to net generation potential assuming 80% capacity factor. It should be noted that, for PV and CSP, the study applied a land constraint of at least 1 km^2 contiguous area. This constraint corresponds to utility-scale solar installation requirements and reflects industry-relevant results.

Within the AMLs and EPA sites, resource potential estimates were produced for all renewable energy technologies mentioned above. Within ACs, all technologies were assessed except hydropower. The hydro resource dataset is very detailed and requires exact location of candidate sites, which is lacking in the AC data. The lack of precise location in the AC data required some accommodation in the analysis for the other renewable energy technologies, but those technology assessments are more regional in nature. Therefore, in estimating potential generation on AC lands, any resource area intersecting AC lands are included in the AC resource calculation, but the available resource area is reduced to the reported AC percentage value. Within transmission line ROWs, resource potential estimates were produced for biomass, PV, and hydropower. For rail and road ROWs only biomass and PV were estimated. All ROWs are considered too narrow or incompatible with utility-scale CSP, geothermal, or wind development; rail and road ROWs are considered too narrow or incompatible with hydropower development. Within barren lands, resource potential was evaluated for all technologies, except biomass. This marginal land category is considered unsuitable for establishing vegetation cover.

Urban areas were excluded in this analysis because most renewable energy technologies are not applicable to populated centers, except PV and some biomass applications. Also, analysis in urban settings would require more precise data, for example the footprint of rooftops or water flow at individual wastewater treatment plants, and such data is difficult to obtain for a nationwide study.

3. Results

The study estimates that marginal lands in the 48 contiguous states cover an area of about 865,000 km^2, about 11% of the contiguous U.S. land. Table 2 shows the different types of marginal

Table 2
Marginal Lands in the Contiguous United States.

Marginal Lands	Area (km^2)
Abandoned Cropland	682,579
Barren Lands	97,418
EPA Sites	47,070
Transmission Lines ROW	28,660
Roads ROW	15,229
Rail ROW	12,046
Abandoned Mine Lands	11,380
Landfills	n/a
Total Marginal Lands	864,826

EPA Sites include Brownfield, Federal/Non-Federal Superfund, and RCRA. ROW: right-of-way. The summary excludes landfills due to lack of data on area covered. Note: The total marginal lands does not sum to total of all categories. This value was calculated separately to avoid double counting of overlapping lands. The summary excludes Alaska and Hawaii.

land and their respective area coverage. ACs are the largest contributor with about 79% of total marginal lands in the 48 contiguous states, followed by barren lands with 11%. As noted earlier, overlapping marginal lands were dissolved to avoid double counting. The team used this technique in the development of state and county summaries as well. Alaska and Hawaii were excluded from the total marginal lands summary due to their remoteness and unlike contributions to the 48 contiguous states' renewable electricity needs. For example, it is very unlikely that transmission lines would be built from Alaska to U.S. mainland given the cost of such development, and the state's vast renewable energy potential most likely won't be fully realized considering the relatively low local demand. The availability of marginal lands in these two states is shown in Table 3. Not surprisingly, large states such as Alaska, Texas and California also have the largest marginal land areas. Georgia, however, is not a particularly large state but it is one of the states with

Table 3
Marginal Lands in the United States by State (km^2).

State	Abandoned Cropland	Abandoned Mines	Barren Lands	EPA Sites	Rail ROW	Roads ROW	Transmission Lines ROW	Total Marginal Lands
AK	0	1	126,784	10	0	18	78	127,173
AL	24,584	4	345	459	237	585	608	26,313
AR	9754	113	190	301	212	276	439	11,129
AZ	6353	59	7014	133	201	392	746	14,639
CA	20,852	80	20,270	6742	465	338	1746	48,893
CO	9120	1143	4183	583	278	498	734	16,013
CT	5831	0	30	28	42	56	80	5948
DC	89	0	0	0	0	0	0	89
DE	884	0	23	29	22	19	46	981
FL	6554	0	901	1740	208	302	645	10,068
GA	51,838	0	492	1385	340	240	810	53,972
HI	0	0	2308	4	0	10	0	2425
IA	7840	21	62	23	346	535	765	9469
ID	3276	114	2853	24	166	93	632	7055
IL	14,387	14	111	120	567	515	714	16,117
IN	14,457	6	75	305	346	142	712	15,696
KS	24,338	186	144	122	499	129	719	25,847
KY	20,976	30	388	557	258	504	598	22,799
LA	11,604	0	348	920	235	437	428	13,703
MA	7060	0	175	46	77	53	106	7377
MD	8007	1	102	24	70	83	166	8298
ME	11,907	2	405	26	102	84	140	12,512
MI	20,494	10	822	42	293	177	606	22,092
MN	7787	0	306	194	352	661	888	10,038
MO	13,218	2269	275	92	335	507	745	17,008
MS	18,282	0	212	33	203	218	444	19,206
MT	6953	2110	2178	3	329	344	741	12,491
NC	17,473	0	403	758	233	216	532	19,225
ND	12,780	0	465	1368	367	181	746	15,743
NE	18,632	46	145	234	354	136	687	20,063
NH	7323	0	92	17	28	44	106	7498
NJ	6290	1	121	156	81	115	143	6669
NM	5435	93	3344	12,951	226	885	667	19,178
NV	594	265	8720	34	153	174	520	10,386
NY	37,054	0	259	930	312	631	546	38,671
OH	27,430	7	205	121	376	702	680	28,935
OK	16,831	168	372	428	263	242	710	18,762
OR	5275	4	3079	30	216	149	756	9338
PA	31,192	3877	450	92	393	281	613	35,084
RI	1176	0	19	8	6	11	11	1207
SC	19,661	5	356	781	196	196	448	21,149
SD	8831	19	1738	131	170	278	604	11,658
TN	16,388	1	212	410	184	195	430	17,557
TX	54,370	36	3514	1534	847	1386	2822	63,473
UT	924	124	24,223	3424	140	114	404	28,852
VA	22,766	284	279	394	268	175	552	24,225
VT	8743	6	39	4	60	46	98	8891
WA	4825	34	2316	1299	270	134	810	9446
WI	11,767	0	112	299	265	526	541	13,302
WV	13,047	239	424	49	223	805	341	14,641
WY	6444	6	2532	21	215	414	619	10,090

Note: EPA Sites include Brownfield, Federal/Non-Federal Superfund, and RCRA. The summary excludes landfills due to lack of data on area covered. ROW: right-of-way. Note: The total marginal lands does not sum to total of all categories. This value was calculated separately to avoid double counting of overlapping lands.

most marginal lands, predominantly ACs. The abandonment could be a result of depopulation of farming areas, climate change (namely the drought that the state has been experiencing for over a decade), increase in forestry activities, market (mal) functioning, land prices, etc. AC is also the main marginal land category in Texas. In Alaska, the marginal lands are almost entirely comprised of barren lands. In the state of California, about half of the marginal lands come from AC and the other half from barren lands with some small contributions from other marginal land categories.

Fig. 1 illustrates the availability of marginal lands by county. Barren lands, EPA sites, and, to some extent, abandoned mines are the main marginal land categories in the West. Abandoned cropland is the main contributor of marginal lands in Eastern counties with some ROWs given the high density of transportation and transmission network in the region. The counties in the Corn Belt and along the Mississippi River have the fewest marginal lands given that they are highly productive and heavily utilized regions.

Table 4 illustrates the estimated renewable energy potential on marginal lands in the contiguous United States. Solar technologies present the highest potential (4.5 PWh from PV, 4 PWh from CSP), followed by wind (2.7 PWh) and biomass power (1.9 PWh). Collectively, the remaining technologies also present a significant renewable energy potential. While it is possible for some technologies to be co-located, it is very likely that only one will be deployed in a given area. Thus, it is most reasonable to view the potential for different technologies separately.

Table 5 presents the results of this analysis by state, and demonstrates the broad distribution of renewable resources throughout the country. The potential for utility-scale PV and CSP generation on marginal lands, considering the land constraint mentioned above, is highest in Utah, California, New Mexico, and Nevada. These are also the top states for potential electricity generation from geothermal. The wind technology on marginal lands appears to be very promising in the states of Texas, Kansas,

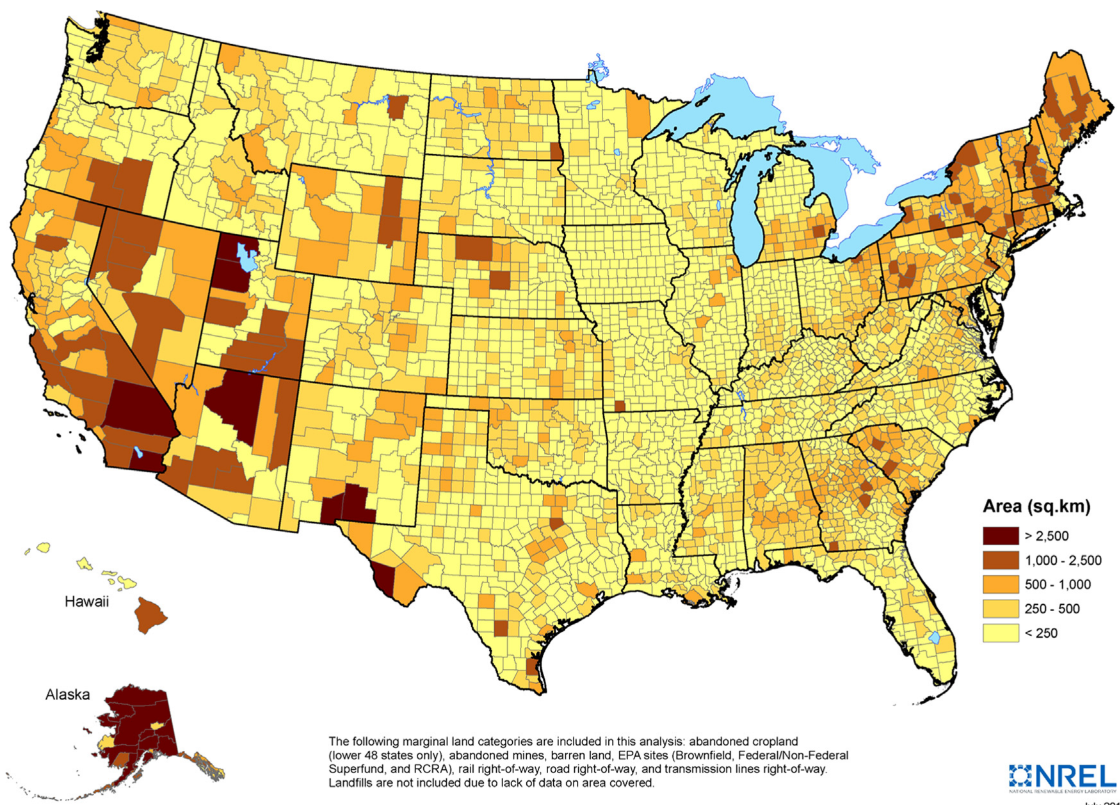

Fig. 1. Marginal Lands in the United States by County.

Table 4
Renewable energy potential on marginal lands in the Contiguous United States.

Marginal Lands	Solar PV		Solar CSP		Geothermal		Wind		Biomass Power		LFG		Hydropower	
	GW	GWh	GW	GWh	GW	GWh	GW	GWh	GW	GWh	GW	GWh	GW	GWh
Transmission Lines ROW	27	54,780	n/a	n/a	n/a	n/a	n/a	n/a	7.5	58,842	n/a	n/a	0.41	1814
Rail ROW	9	18,594	n/a	n/a	n/a	n/a	n/a	n/a	3.5	27,868	n/a	n/a	n/a	n/a
Roads ROW	3	7570	n/a	n/a	n/a	n/a	n/a	n/a	4.4	34,930	n/a	n/a	n/a	n/a
Abandoned Mine Lands	44	75,898	3	10,216	0.02	188	4.8	14,737	3.4	26,852	n/a	n/a	0.2	870
Barren Lands	1415	2,880,099	936	2,961,373	0.57	4514	25	83,116	n/a	n/a	n/a	n/a	1.6	6898
Abandoned Cropland	11,619	19,490,945	1665	4,909,197	0.34	2652	712	2,519,455	226	1,784,474	n/a	n/a	–	–
EPA Sites	837	1,650,264	370	1,241,204	0.21	1669	14.7	48,749	5.2	40,924	n/a	n/a	0.2	924
Landfills	–	–	–	–	–	–	–	–	–	–	1	7267	–	–
Total	2264	4,538,017	1264	4,060,913	1.12	8848	752	2,650,745	246	1,936,679	1	7267	2.4	10,946

"n/a" not applicable. "–" insufficient data. Note: Solar PV and CSP illustrate the results of the filtered analysis considering only lands with more than 1 km^2 continuous area. Biomass power includes the potential from dedicated herbaceous energy crops only. The summary excludes Alaska and Hawaii.

Table 5
Renewable energy potential on marginal lands in the United States by State.

State	Solar PV		Solar CSP		Geothermal		Wind		Biomass Power		LFG		Hydropower	
	GW	GWh	GW	GWh	GW	GWh	GW	GWh	GW	GWh	GW	GWh	GW	GWh
AK	91	80,071	0	0	0	0	49	181,866	–	–	0.004	25	0.9	4068
AL	7.6	12,609	0	0	0	0	0.03	72	11	86,349	0.04	293	0.02	98
AR	5.6	9199	0	0	0	0	0.5	1537	4.8	37,619	0.008	53	0.07	318
AZ	89	197,732	59	210,929	0.04	282	0.8	2353	0.008	65	0.03	184	0.013	58
CA	394	869,825	262	930,180	0.35	2782	5	15,792	1	8056	0.09	647	0.3	1472
CO	7.4	14,796	4.6	14,196	0.07	523	18	60,333	0.3	2668	0.03	185	0.05	213
CT	0	0	0	0	0	0	0.008	22	2.5	19,882	0.004	25	0.012	51
DC	0	0	0	0	0	0	0	0	0.02	187	0	0	0	0
DE	0.2	318	0	0	0	0	0	0.3	0.3	2295	0	0	0	0.2
FL	39	67,579	0	0	0	0	0	0	3.6	28,209	0.05	334	0.018	79
GA	34	57,091	0	0	0	0	0.03	87	18.6	147,008	0.04	298	0.014	62
HI	2.6	5520	1.4	3848	0	0	0.5	1914	–	–	0.01	69	0.013	58
IA	0.3	434	0	0	0	0	31	108,305	3.8	30,133	0.016	111	0.004	17
ID	19	35,202	12	34,254	0.05	394	0.3	907	0.2	1766	0.003	22	0.05	214
IL	2.5	3687	0	0	0	0	23	71,273	7.6	59,746	0.06	442	0.001	2.7
IN	2.7	4036	0	0	0	0	13	37,867	7.3	57,495	0.03	238	0.067	293
KS	9.7	16,241	0.04	115	0	0	107	397,406	8.3	65,621	0.01	78	0.018	79
KY	9	14,318	0	0	0	0	0.01	36	9.5	75,220	0.036	249	0.065	286
LA	14	22,346	0	0	0	0	0.03	73	5.2	41,140	0.02	145	0.011	48
MA	0.3	399	0	0	0	0	0.28	844	1.6	12,334	0.002	15	0	2
MD	0.1	170	0	0	0	0	0.10	275	3.4	27,025	0.02	147	0.003	11
ME	0.3	463	0	0	0	0	1.2	3661	3.9	30,533	0.006	43	0.037	164
MI	2.7	3993	0	0	0	0	9	25,538	9.2	72,157	0.01	83	0.011	49
MN	8	12,005	0	0	0	0	18	64,084	3.1	24,438	0.007	49	0.005	21
MO	19	32,307	0	0	0	0	28	82,064	7.2	56,715	0.04	291	0.061	265
MS	1.4	2368	0	0	0	0	0	0	8.6	67,483	0.03	193	0.036	158
MT	13	21,261	0.7	1840	0.03	202	22	77,265	0.06	488	0.004	26	0.133	583
NC	16	25,775	0	0	0	0	0.10	296	6.9	54,730	0.04	302	0.004	17
ND	49	74,740	0	0	0	0.001	61	235,475	1.3	10,521	0.001	6	0	0.5
NE	9	15,757	0.7	1987	0	0.003	86	332,320	5.6	44,473	0.008	58	0.013	57
NH	0	0	0	0	0	0	0.5	1572	2.2	16,971	0.003	23	0.002	6.7
NJ	2.3	3546	0	0	0	0	0.005	13	2.5	19,344	0.001	10	0.001	6.4
NM	362	793,555	235	807,511	0.13	1035	16	52,802	0.4	3126	0.004	26	0.003	14
NV	278	571,282	183	570,975	0.15	1184	0.1	281	0.001	10	0.007	47	0.006	25
NY	13	18,384	0	0	0	0	8.7	25,142	13.2	103,745	0.01	80	0.027	117
OH	2.3	3374	0	0	0	0	4.3	11,878	11.9	93,617	0.06	397	0.052	228
OK	19	33,042	5.6	15,463	0	0	60	206,330	5.8	45,939	0.03	181	0.048	209
OR	29	55,314	19	51,852	0.06	480	0.3	915	1.5	11,557	0.002	13	0.245	1071
PA	0.3	366	0	0	0	0	0.8	2421	17.4	137,263	0.03	233	0.088	386
PR	0	0	0	0	0	0	0	0	0	0	0.03	215	0	0
RI	0	0	0	0	0	0	0.003	11	0.4	3505	0	0	0	0.3
SC	14	23,486	0	0	0	0	0.02	53	7.8	61,601	0.009	64	0.054	239
SD	9.6	15,592	3.4	9531	0	0.001	45	178,341	2.0	15,605	0.002	16	0.011	48
TN	6.6	10,465	0	0	0	0	0.04	127	7.7	60,697	0.017	117	0.134	588
TX	86	174,727	39	129,709	0	0.49	150	516,312	12.9	101,317	0.14	950	0.037	161
UT	645	1,246,313	432	1,264,952	0.23	1790	1.3	3454	0.02	159	0.007	48	0.01	43
VA	6.2	9809	0	0	0	0	0.4	1086	9.6	75,658	0.01	89	0.009	39
VI	0	0	0	0	0	0	0	0	0	0	0.002	12	0	0
VT	0	0	0	0	0	0	0.9	2653	2.8	22,393	0	0	0.009	41
WA	27	44,815	2.8	7653	0.01	113	1	3013	1	7622	0.009	64	0.5	2334
WI	5.7	8426	0	0	0	0	12	35,747	5.4	42,871	0.005	36	0.009	39
WV	0.2	223	0	0	0	0	0.3	959	6.2	49,156	0.015	103	0.03	137
WY	4	7662	3.5	9687	0.008	62	25	88,642	0.02	168	0.004	25	0.03	143

Note: Solar PV and CSP illustrate the results of the filtered analysis considering only lands with more than 1 km^2 continuous area. Biomass power includes the potential from dedicated herbaceous energy crops only. "–" insufficient data.

Nebraska, North Dakota, and Oklahoma. The energy potential from dedicated herbaceous energy crops on marginal lands is very high in Georgia, Pennsylvania, New York, and Texas. The potential for LFG is concentrated in highly populated states such as Texas, California, Illinois, Ohio, and Florida. The potential for mini-hydro on marginal lands is highest in Alaska, Washington, California, and Oregon.

The county-level distribution of the renewable energy potential on marginal lands follows closely the resource patterns (Fig. 2). The potential for wind development is concentrated in the Great Plains. PV, CSP and geothermal are prominent in the West; biomass is predominant in the East. Opportunities for hydro and LFG development are scattered throughout the country.

4. Discussion and conclusions

The authors find significant potential for renewable energy development on marginal U.S. land. To put things in perspective, the United States consumed roughly 4 PWh of electricity in 2011 [12]. According to the results of our study, this amount of electricity could be produced on marginal lands from PV or CSP alone. Therefore, renewable energy development on these lands could play an important role in increasing the country's domestic energy supply. Renewable energy sources provided about 13% of total U.S. utility-scale electricity generation in 2011 [13]. Marginal lands provide an opportunity for increasing the share of renewables in the country's energy mix and meeting clean energy

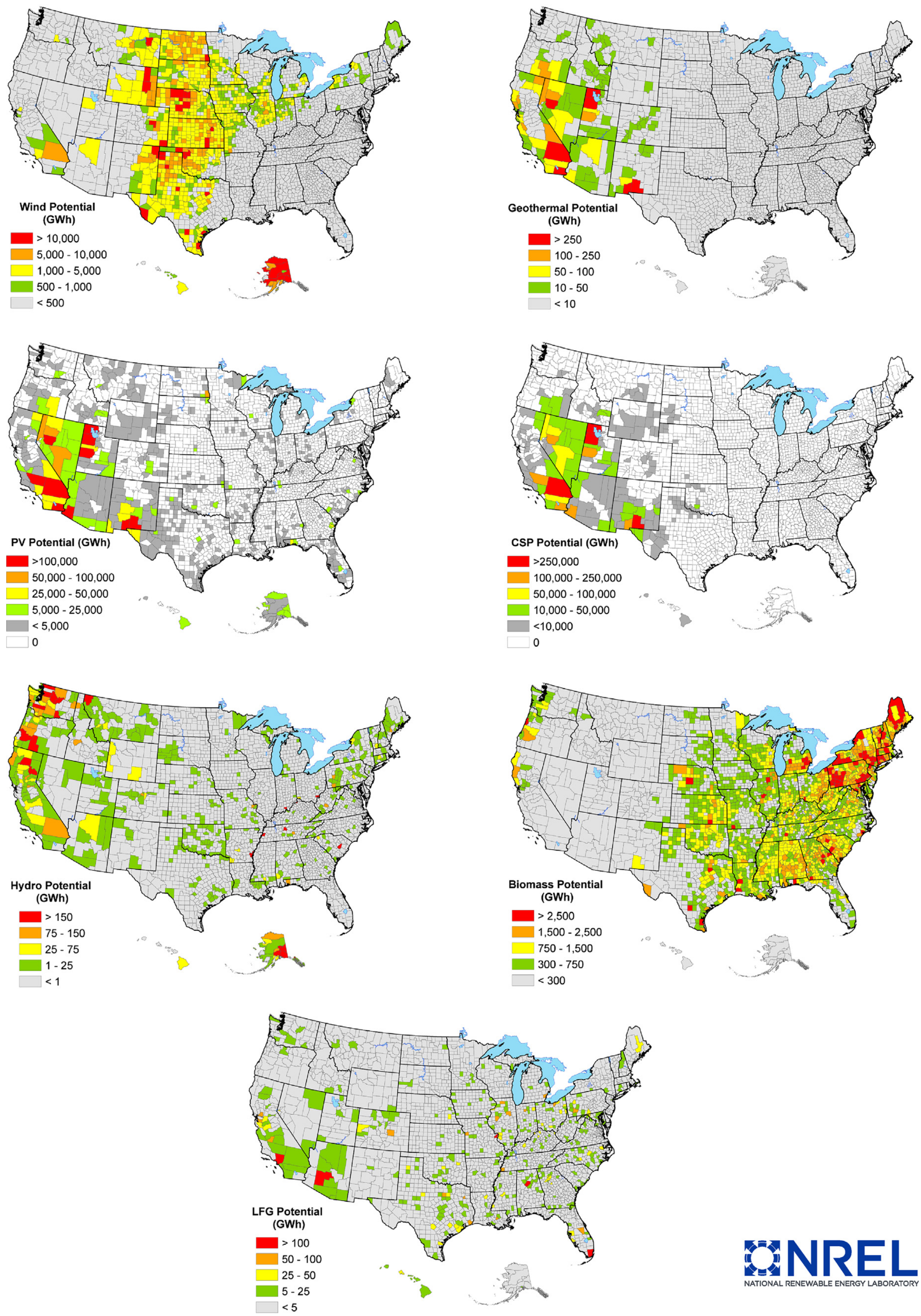

Fig. 2. Renewable Energy Potential on Marginal Lands in the United States by County. *Note*: PV and CSP maps show solar potential on marginal lands with at least1 km^2 contiguous area. Biomass potential includes dedicated herbaceous energy crops only.

targets. These lands are particularly promising for solar technologies but also hold a great potential for wind and biomass expansion. The study estimates that about 4.5 PWh of electricity could be generated from PV on marginal lands in the 48 contiguous states. In comparison, electricity generation from both PV and CSP in 2011 was estimated at 1.8 TWh [14].

It is unrealistic to assume that all of the renewable energy potential on marginal lands could be realized, but if even half of that potential is developed, it still can contribute substantially to the U.S. energy portfolio. Different technologies may have to compete for development on these lands, although some could co-exist, such as wind generation and energy crops production. The competition among renewable energy technologies on marginal lands is reduced to a large extent by the nature of resource distribution: solar resources are dominant in the Southwest, micro-hydro in the Northwest, wind in Central Plains, and biomass in the East. Candidate landfills are scattered throughout the country and generally LFG-to-electricity projects are not in competition with other technologies. In fact, these facilities are seen as a good opportunity for co-locating other renewable energy installations such as PV. Competition for land could occur between solar and geothermal technologies given that both solar and geothermal resources are concentrated in the West.

Several caveats need to be noted in this study. There is some degree of uncertainty associated with the analysis due to lack of data on specific area covered for select marginal lands. Conservative estimates were used to compensate for this uncertainty. Also, additional marginal land categories, such as saline lands and degraded forests, fell beyond the scope of this study. Detailed data on the location and size of lands under the Conservation Reserve Program (CRP) are not readily available, which prevented this category from inclusion in the analysis. CRP is a voluntary program where landowners enroll in contracts to take highly erodible or environmentally sensitive lands out of agricultural production and put them into other uses such as establishing permanent vegetative cover (e.g. native grasses) or wildlife refuges. While the study applies numerous environmental exclusions, it may not capture all local areas of biodiversity conservation due to gaps that naturally exist in nationwide data. Detailed analysis at a given location would reveal best the local ecology and identify additional sensitive areas unsuitable for development. It should also be noted that renewable energy installations may already exist on some of the evaluated lands, particularly on ACs and barren lands. This study does not estimate how much, if any, of the marginal land potential may have already been utilized. For certain marginal land categories, namely ROWs, it is safe to assume that limited or no development has occurred. We would like to mention that the potential for biofuels was not evaluated here primarily to allow a direct comparison between the different renewable energy technologies. Another reason is that there are many different feedstocks (lignocellulosic material and oil-bearing crops), conversion pathways, and final products (cellulosic ethanol; biodiesel; drop-in fuels such as renewable gasoline, diesel, and jet fuel) that need to be considered, all of which would be better covered in a follow-on or separate study. We would also like to note that this analysis is a snapshot of the currently available marginal lands. Subsequent studies could look into projected land use/cover changes and assess the availability of these lands in the future.

Despite the study's limitations listed above, the authors believe that the findings of this work can serve as a base for further, more detailed analyses. In addition to improving the quality of existing database, future work could include evaluation of additional marginal land categories, an in-depth analysis of a particular marginal land category, and site-specific feasibility studies. An economic analysis of renewable energy installations on these lands would also be beneficial: for example, the cost of infrastructure development (e.g. roads and transmission lines) for some sites could be restrictive or prohibitive; while for others, federal/state tax incentives and credits available under cleanup, redevelopment and reuse programs could provide attractive investment opportunities. In the area of biomass analysis, an improvement could be made by including additional resources such as drought-tolerant species suitable in the West, dedicated woody energy crops, and plants suitable to the agro-climatic conditions of Alaska and Hawaii.

As the development of renewable energy in the United States is projected to grow so is the need for land to support this development. Marginal lands have the potential to contribute to the country's clean energy economy and decrease the pressure on valuable land resources. Given that some of these lands may contain intact natural systems, not necessarily on environmentally sensitive or protected area records, thorough evaluation of the present ecology would ensure that marginal lands development is done in harmony with the local environment. Relevant policies would also be needed to assure that renewable energy installations on marginal lands result in the fewest impacts possible on the natural resources.

Acknowledgments

The authors acknowledge the support of the Joint Institute for Strategic Energy Analysis, which is operated by the Alliance for Sustainable Energy, LLC, on behalf of the U.S. Department of Energy's National Renewable Energy Laboratory, the University of Colorado-Boulder, the Colorado School of Mines, the Colorado State University, the Massachusetts Institute of Technology, and Stanford University. Melissa Wiggins from the National Renewable Energy Laboratory (NREL) assisted in the data-gathering process and Nick Grue, also from NREL, supported the geospatial analysis. We would also like to thank Elliott Campbell, assistant professor in the School of Engineering at the University of California – Merced, for providing valuable data and information.

References

[1] Schmidt J, Haifly A. Delivering on renewable energy around the World; Natural Resources Defense Council: Washington, DC, 2012. Available from: 〈http://www.nrdc.org/energy/files/delivering-renewable-energy.pdf〉.
[2] Newton GA, Claassen VP. Rehabilitation of disturbed lands in California: a manual for decision-making, California Geological Survey: Sacramento, CA, 2003. Available from: 〈www.conservation.ca.gov/omr/reclamation/Documents/sp123.pdf〉.
[3] Mosey G, Heimiller D, Dahle D, Vimmerstedt L, Brady-Sabeff L. Converting Limbo Lands to Energy-Generating Stations: Renewable Energy Technologies on Underused, Formerly Contaminated Sites. Golden, CO: National Renewable Energy Laboratory; 2007. 〈http://www.epa.gov/nrmrl/pubs/600r08023.html〉.
[4] Fuchs C. UN convention to combat desertification: recent developments. Leiden, The Netherlands: Max Planck Yearbook of United Nations Law; 287–300.
[5] Zumkehr A, Campbell E. Historical U.S. Cropland Areas and the Potential for Bioenergy Production on Abandoned Croplands. Environmental Science and Technology 2013;47(8):3840–7.
[6] U.S. Environmental Protection Agency. Landfill Methane Outreach Program; Washington, DC, 2012. Available from: 〈http://www.epa.gov/lmop/index.html〉.
[7] Tennessee Valley Authority. Standard Right of Way Widths; Knoxville, TN, 2012. Available from: 〈http://www.tva.com/power/rightofway/faq.htm〉.
[8] United States Geological Survey. National Land Cover Database 2006. Available from: 〈http://www.mrlc.gov/nlcd2006.php〉.
[9] Lopez A, Roberts B, Heimiller D, Blair N, Porro G. U.S. renewable energy technical potentials: a GIS-based analysis. Golden, CO: National Renewable Energy Laboratory; 2012. 〈http://www.nrel.gov/docs/fy12osti/51946.pdf〉.
[10] Energy Biosciences Institute. Biofuel Ecophysiological Traits and Yields Database. Available from: 〈https://www.betydb.org/〉.
[11] Laurence Eaton, Oak Ridge National Laboratory (ORNL), Personal Communication. The data was used in the development of the "U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry", August 2011.

Available from: ⟨http://www1.eere.energy.gov/biomass/pdfs/billion_ton_update.pdf⟩.
[12] U.S. Energy Information Administration. Use of Electricity; Washington, DC, 2012. Available from: ⟨http://www.eia.gov/energyexplained/index.cfm?page=electricity_use⟩.
[13] U.S. Energy Information Administration. Energy in Brief; Washington, DC, 2012. Available from: ⟨http://www.eia.gov/energy_in_brief/renewable_electricity.cfm⟩.
[14] U.S. Energy Information Administration. Monthly Energy Review; Washington, DC, 2012. Available from: ⟨http://www.eia.gov/totalenergy/data/monthly/⟩.